

Holographic tachyon model

Jingfei Zhang,¹ Xin Zhang,² and Hongya Liu¹

¹*School of Physics and Optoelectronic Technology,*

Dalian University of Technology, Dalian 116024, People's Republic of China

²*Kavli Institute for Theoretical Physics China, Institute of Theoretical Physics,*

Chinese Academy of Sciences (KITPC/ITP-CAS),

P.O.Box 2735, Beijing 100080, People's Republic of China

We propose in this Letter a holographic model of tachyon dark energy. A connection between the tachyon scalar-field and the holographic dark energy is established, and accordingly, the potential of the holographic tachyon field is constructed. We show that the holographic evolution of the universe with $c \geq 1$ can be described completely by the resulting tachyon model in a certain way.

The astronomical observations over the past decade indicate that our universe is currently undergoing an epoch of accelerated expansion (see e.g. Refs. [1, 2, 3]). Such an accelerated expansion implies, following the Friedmann-Robertson-Walker (FRW) cosmology, the existence of a “dark energy”, a mysterious exotic matter with large enough negative pressure, whose energy density has been a dominative power of the universe. The astrophysical feature of dark energy is that it remains unclustered at all scales where gravitational clustering of baryons and non-baryonic cold dark matter can be seen. Its gravity effect is shown as a repulsive force so as to make the expansion of the universe accelerate when its energy density becomes dominative power of the universe. The combined analysis of cosmological observations suggests that the universe is spatially flat, and consists of about 70% dark energy, 30% dust matter (cold dark matter plus baryons), and negligible radiation. The most obvious candidate for the dark energy is the cosmological constant λ [4] for which $w = -1$ (for reviews see e.g. Refs. [5]). However, the cosmological constant always suffers from the “fine-tuning” and “cosmic coincidence” problems. Another candidate for dark energy is the energy density associated with dynamical scalar-field, a slowly varying, spatially homogeneous component. An example of scalar-field dark energy is the so-called “quintessence” [6], a scalar field Q slowly evolving down its potential $V(Q)$. Provided that the evolution of the field is slow enough, the kinetic energy density is less than the potential energy density, giving rise to the negative pressure responsible to the cosmic acceleration. So far a wide variety of scalar-field dark energy models have been proposed. Besides quintessence, these also include phantom [7], K -essence [8], tachyon [9], ghost condensate [10] and quintom [11] amongst many. But we should note that the mainstream viewpoint regards the scalar field dark energy models as an effective description of an underlying theory of dark energy. In addition, other proposals on dark energy include interacting dark energy models [12], braneworld models [13], and Chaplygin gas models [14], etc.. One should realize, nevertheless, that almost these models are settled at the phenomenological level, lacking theoretical root.

In recent years, many string theorists have devoted to

understand and shed light on the cosmological constant or dark energy within the string framework. The famous Kachru-Kalosh-Linde-Trivedi (KKLT) model [15] is a typical example, which tries to construct metastable de Sitter vacua in the light of type IIB string theory. Furthermore, string landscape idea [16] has been proposed for shedding light on the cosmological constant problem based upon the anthropic principle and multiverse speculation. Another way of endeavoring to probe the nature of dark energy within the fundamental theory framework originates from some considerations of the features of the quantum gravity theory. It is generally believed by theorists that we can not entirely understand the nature of dark energy before a complete theory of quantum gravity is established. However, although we are lacking a quantum gravity theory today, we still can make some attempts to probe the nature of dark energy according to some principles of quantum gravity. The holographic dark energy model [17, 18, 19] is just an appropriate example, which is constructed in the light of the holographic principle [20] of quantum gravity theory. That is to say, the holographic dark energy model possesses some significant features of an underlying theory of dark energy.

According to the holographic principle, the number of degrees of freedom for a system within a finite region should be finite and should be bounded roughly by the area of its boundary. In the cosmological context, the holographic principle will set an upper bound on the entropy of the universe. Motivated by the Bekenstein entropy bound, it seems plausible to require that for an effective quantum field theory in a box of size L with UV cutoff Λ , the total entropy should satisfy $S = L^3 \Lambda^3 \leq S_{BH} \equiv \pi M_P^2 L^2$, where S_{BH} is the entropy of a black hole with the same size L . However, Cohen et al. [17] pointed out that to saturate this inequality some states with Schwarzschild radius much larger than the box size have to be counted in. As a result, a more restrictive bound, the energy bound, has been proposed to constrain the degrees of freedom of the system, requiring that the total energy of a system with size L should not exceed the mass of a black hole with the same size, namely, $L^3 \Lambda^4 = L^3 \rho_\Lambda \leq L M_P^2$. This means that the maximum entropy is in order of $S_{BH}^{3/4}$. When we take the

whole universe into account, the vacuum energy related to this holographic principle is viewed as dark energy, usually dubbed holographic dark energy. The largest IR cut-off L is chosen by saturating the inequality so that we get the holographic dark energy density

$$\rho_\Lambda = 3c^2 M_P^2 L^{-2}, \quad (1)$$

where c is a numerical constant, and $M_P \equiv 1/\sqrt{8\pi G}$ is the reduced Planck mass. Many authors have devoted to develop the idea of the holographic dark energy (see e.g. Refs. [21]). It has been conjectured by Li [19] that the IR cutoff L should be given by the future event horizon of the universe

$$R_{\text{eh}}(a) = a \int_t^\infty \frac{dt'}{a(t')} = a \int_a^\infty \frac{da'}{Ha'^2}. \quad (2)$$

Such a holographic dark energy looks reasonable, since it may provide simultaneously natural solutions to both dark energy problems as demonstrated in Ref.[19]. The holographic dark energy model has been tested and constrained by various astronomical observations [22].

The holographic dark energy scenario reveals the dynamical nature of the vacuum energy. When taking the holographic principle into account, the vacuum energy density will evolve dynamically. On the other hand, let us consider another dynamical dark energy candidate, the scalar-field dark energy. The scalar field dark energy models are often viewed as effective description of the underlying theory of dark energy. However, the underlying theory of dark energy can not be achieved before a complete theory of quantum gravity is established. We can, nevertheless, speculate on the underlying theory of dark energy by taking some principles of quantum gravity into account. The holographic dark energy model is no doubt a tentative in this way. We are now interested in that if we assume the holographic vacuum energy scenario as the underlying theory of dark energy, how the scalar field model can be used to effectively describe it. In this direction, some work has been done. The issues of holographic quintessence and holographic quintom have been discussed in Refs. [23] and [24]. In this Letter, we will construct the holographic tachyon model, connecting the tachyon scalar-field with the holographic dark energy.

The rolling tachyon condensate in a class of string theories may have interesting cosmological consequences. It has been shown by Sen [9] that the decay of D-branes produces a pressureless gas with finite energy density that resembles classical dust. A rolling tachyon has an interesting equation of state whose parameter smoothly interpolates between -1 and 0 [25]. Thus, tachyon can be viewed as a suitable candidate for the inflaton at high energy [26]. Meanwhile, the tachyon can also act as a source of dark energy depending upon the form of the tachyon potential [27]. We shall consider a tachyon model with definite holography nature in this Letter. In what follows we shall construct the holographic tachyon potential according to the holographic evolution of the universe. The

effective Lagrangian for the tachyon on a non-BPS D3-brane is described by

$$S = - \int d^4x V(\phi) \sqrt{-\det(g_{ab} + \partial_a \phi \partial_b \phi)}, \quad (3)$$

where $V(\phi)$ is the tachyon potential. The corresponding energy momentum tensor has the form

$$T_{\mu\nu} = \frac{V(\phi) \partial_\mu \phi \partial_\nu \phi}{\sqrt{1 + g^{\alpha\beta} \partial_\alpha \phi \partial_\beta \phi}} - g_{\mu\nu} V(\phi) \sqrt{1 + g^{\alpha\beta} \partial_\alpha \phi \partial_\beta \phi}. \quad (4)$$

In a flat FRW background the energy density ρ_t and the pressure density p_t are given by

$$\rho_t = -T_0^0 = \frac{V(\phi)}{\sqrt{1 - \dot{\phi}^2}}, \quad (5)$$

$$p_t = T_i^i = -V(\phi) \sqrt{1 - \dot{\phi}^2}. \quad (6)$$

The equation of state of the tachyon is consequently given by

$$w_t = p_t/\rho_t = \dot{\phi}^2 - 1. \quad (7)$$

We see that irrespective the steepness of the tachyon potential, the equation of state varies between 0 and -1 . Clearly, the tachyonic scalar field cannot realize the equation of state crossing -1 .

Imposing the holographic nature to the tachyon, the energy density of tachyon is needed to satisfy the requirement of holographic principle, i.e., we should identify ρ_t with ρ_Λ . It is remarkable that here the condition $c \geq 1$ is needed as will be discussed below. Consider a universe filled with matter component ρ_m (including both baryon matter and cold dark matter) and holographic tachyon component ρ_t , the Friedmann equation reads

$$3M_P^2 H^2 = \rho_m + \rho_t, \quad (8)$$

or equivalently,

$$H(z) = H_0 \left(\frac{\Omega_{m0}(1+z)^3}{1 - \Omega_t} \right)^{1/2}, \quad (9)$$

where $z = (1/a) - 1$ is the redshift of the universe. Note that we always assume spatial flatness throughout this Letter as motivated by inflation. Combining the definition of the holographic dark energy (1) and the definition of the future event horizon (2), we derive

$$\int_a^\infty \frac{d \ln a'}{H a'} = \frac{c}{H a \sqrt{\Omega_t}}. \quad (10)$$

We notice that the Friedmann equation (9) implies

$$\frac{1}{H a} = \sqrt{a(1 - \Omega_t)} \frac{1}{H_0 \sqrt{\Omega_{m0}}}. \quad (11)$$

Substituting (11) into (10), one obtains the following equation

$$\int_x^\infty e^{x'/2} \sqrt{1 - \Omega_t} dx' = ce^{x/2} \sqrt{\frac{1}{\Omega_t} - 1}, \quad (12)$$

where $x = \ln a$. Then taking derivative with respect to x in both sides of the above relation, we get easily the dynamics satisfied by the dark energy, i.e. the differential equation about the fractional density of dark energy,

$$\Omega_t' = -(1+z)^{-1} \Omega_t (1 - \Omega_t) \left(1 + \frac{2}{c} \sqrt{\Omega_t}\right), \quad (13)$$

where the prime denotes the derivative with respect to the redshift z . This equation describes behavior of the holographic dark energy completely, and it can be solved exactly [19]. From the energy conservation equation of the dark energy, the equation of state of the dark energy can be given

$$w_t = -1 - \frac{1}{3} \frac{d \ln \Omega_t}{d \ln a} = -\frac{1}{3} \left(1 + \frac{2}{c} \sqrt{\Omega_t}\right). \quad (14)$$

Note that the formula $\rho_t = \frac{\Omega_t}{1 - \Omega_t} \rho_m^0 a^{-3}$ and the differential equation of Ω_t (13) are used in the second equal sign. Using Eqs. (5), (7) and (9), we derive the holographic tachyon potential

$$\frac{V(\phi)}{\rho_{c0}} = \frac{\Omega_t \Omega_{m0} (1+z)^3}{1 - \Omega_t} \sqrt{-w_t}, \quad (15)$$

where Ω_t and w_t are given by Eqs. (13) and (14), $\rho_{c0} = 3M_P^2 H_0^2$ is today's critical density of the universe. Furthermore, using Eqs. (7) and (9), the derivative of the holographic tachyon scalar-field ϕ with respect to the redshift z can be given

$$\frac{\phi'}{H_0^{-1}} = \pm \sqrt{\frac{(1 - \Omega_t)(1 + w_t)}{\Omega_{m0}(1+z)^5}}, \quad (16)$$

where the sign is actually arbitrary since it can be changed by a redefinition of the field, $\phi \rightarrow -\phi$. Consequently, we can easily obtain the evolutionary form of the holographic tachyon field

$$\phi(z) = \int_0^z \phi' dz, \quad (17)$$

by fixing the field amplitude at the present epoch ($z = 0$) to be zero, $\phi(0) = 0$.

The property of the holographic dark energy is mainly governed by the numerical parameter c . From Eq. (14), it can be easily found that the evolution of the equation of state satisfies $-(1 + 2/c)/3 \leq w \leq -1/3$ due to $0 \leq \Omega_t \leq 1$. Thus, the parameter c plays a significant role in the holographic evolution of the universe. When $c < 1$, the holographic evolution will make the equation

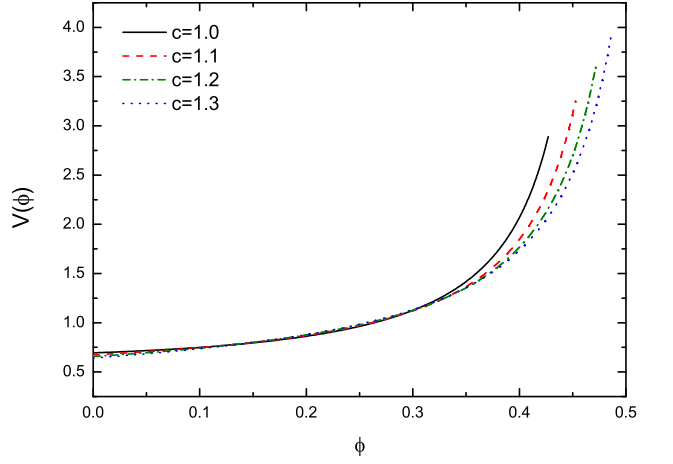


FIG. 1: The potential for the holographic tachyon, where ϕ is in unit of H_0^{-1} and $V(\phi)$ in ρ_{c0} . We take here $\Omega_{m0} = 0.27$.

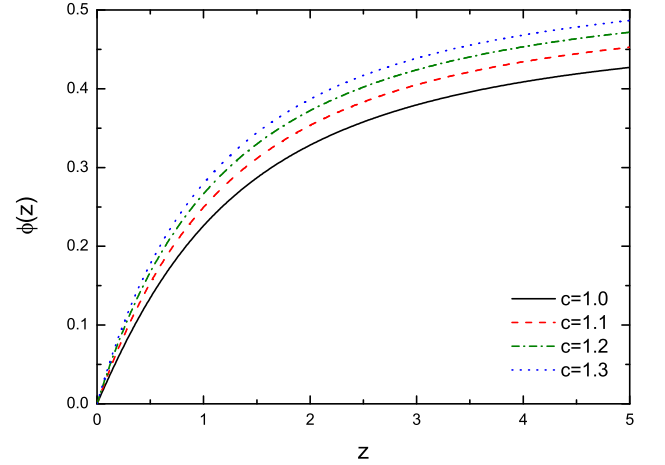


FIG. 2: The evolution of the scalar-field $\phi(z)$ for the holographic tachyon, where ϕ is in unit of H_0^{-1} . We take here $\Omega_{m0} = 0.27$.

of state cross $w = -1$ (from $w > -1$ evolves to $w < -1$); when $c \geq 1$, the equation of state will evolve in the region of $-1 \leq w \leq -1/3$. Since the equation of state of tachyon scalar-field evolves within the range of $-1 < w < 0$, only the holographic evolution of cases $c \geq 1$ can be described by the tachyon. So, it is notable that the constructed holographic tachyon, Eqs. (15)-(17), must satisfy the condition $c \geq 1$. In fact, in the holographic scenario, the value of c should be determined by cosmological observations. However, current observational data cannot determine the value of c accurately due to the precision of these data. An analysis of the latest observational data, including the gold sample of 182 SNIa, the CMB shift parameter given by the 3-year WMAP observations, and the BAO measurement from the SDSS, shows that the possibilities of $c > 1$ and $c < 1$ both exist and their

likelihoods are almost equal within 3 sigma error range [28].

The tachyon models with different potential forms have been discussed widely in the literature. For the holographic tachyon model constructed in this Letter, the potential $V(\phi)$ can be determined by Eqs. (15)-(17). The analytical form of the potential $V(\phi)$ cannot be derived due to the complexity of these equations, but we can obtain the holographic tachyon potential numerically. Using the numerical method, the holographic tachyon potential $V(\phi)$ is plotted in figure 1, where $\phi(z)$ is also obtained according to Eqs. (16) and (17), also displayed in figure 2. Selected curves are plotted for the cases of $c = 1.0, 1.1, 1.2$ and 1.3 , and the present fractional matter density is chosen to be $\Omega_{m0} = 0.27$. From figures 1 and 2, we can see the dynamics of the tachyon scalar field explicitly. According to the holographic evolution of the universe, the tachyon potential is more steep in the early epoch ($z \sim 5$) and becomes very flat near today. Consequently, the tachyon scalar field ϕ rolls down the potential with the kinetic energy $\dot{\phi}^2$ gradually decreasing. The equation of state of the tachyon w_t , accordingly, decreases gradually with the cosmic evolution, and as a result $dw_t/d\ln a < 0$. This feature is very similar to the holographic quintessence, see Ref.[23] for details.

In summary, we have proposed in this Letter a holographic model of tachyon dark energy. We adopt the viewpoint of that the scalar field models of dark energy are effective theories of an underlying theory of dark

energy. The underlying theory, though has not been achieved presently, is presumed to possess some features of a quantum gravity theory, which can be explored speculatively by taking into account the holographic principle of quantum gravity theory. If we regard the tachyon scalar-field as an effective description of the underlying theory of dark energy, it should, presumably, carry some holographic feature. Naturally, the tachyon with holographic feature should be capable of realizing the holographic evolution of the universe. We show that the holographic evolution of the universe with $c \geq 1$ can be described completely by the tachyon in a certain way. A connection between the tachyon and the holographic dark energy has been established, and the potential of the holographic tachyon has been constructed accordingly.

Acknowledgements

This work is supported by the China Postdoctoral Science Foundation, the K. C. Wong Education Foundation (Hong Kong), the National Natural Science Foundation of China, as well as the National Basic Research Program of China (2003CB716300).

Note Added: During the submission and review process of this manuscript, Ref. [29] appeared on the arXiv which discusses the similar topic to our study.

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